

# The Crab pulsar seen with Aqueye at Asiago Cima Ekar Observatory

L. Zampieri <sup>a,\*</sup>, C. Germanà <sup>b,a</sup>, C. Barbieri <sup>b</sup>, G. Naletto <sup>c,d</sup>,  
A. Čadež <sup>e</sup>, I. Capraro <sup>c,b</sup>, A. Di Paola <sup>f</sup>, C. Facchinetti <sup>b</sup>,  
T. Occhipinti <sup>c,b</sup>, D. Ponikvar <sup>e</sup>, E. Verroi <sup>b,c</sup> and P. Zoccarato <sup>g,b</sup>

<sup>a</sup>*INAF-Astronomical Observatory of Padova, Vicolo dell'Osservatorio 5, 35122  
Padova, Italy*

<sup>b</sup>*Astronomy Department, University of Padova, Vicolo dell'Osservatorio 2, 35122  
Padova, Italy*

<sup>c</sup>*Department of Information Engineering, University of Padova, Via Gradenigo  
6/B, 35131 Padova, Italy*

<sup>d</sup>*CNR/INFM/LUXOR, via Gradenigo 6/B, 35131 Padova, Italy*

<sup>e</sup>*Faculty of Mathematics and Physics, University of Ljubljana, Jadranska 19, 1000  
Ljubljana, Slovenia*

<sup>f</sup>*INAF-Astronomical Observatory of Rome, Via frascati 33, 00040 Monteporzio  
Catone (Roma), Italy*

<sup>g</sup>*Interdipartimental Center of Studies and Activities for Space (CISAS) "G.  
Colombo", University of Padova, Via Venezia 15, 35131 Padova, Italy*

---

## Abstract

We are developing fast photon-counter instruments to study the rapid variability of astrophysical sources by time tagging photon arrival times with unprecedented accuracy, making use of a Rubidium clock and GPS receiver. The first realization of such optical photon-counters, dubbed Aqueye (the Asiago Quantum Eye), was mounted in 2008 at the 182cm Copernicus Observatory in Asiago. Aqueye observed the Crab pulsar several times and collected data of extraordinary quality that allowed us to perform accurate optical timing of the Crab pulsar and to study the pulse shape stability on a timescale from days to years with an excellent definition. Our results reinforce the evidence for decadal stability of the inclination angle between the spin and magnetic axis of the Crab pulsar. Future realizations of our instrument will make use of the Galileo Global Navigation Satellite System (GNSS) time signal.

*Key words:* Pulsars: general; Pulsars: individual PSR J0534+2200 (Crab pulsar); Pulsar timing

---

## 1 Introduction

The pulsar in the Crab Nebula (PSR J0534+2200) is one of the best studied objects in the sky. It is the brightest optical pulsar and the first to be detected in the optical band (Cocke et al., 1969; Lynds et al., 1969). The pulse shape of the Crab pulsar was investigated in various photometric bands (e.g. Percival et al., 1993; Lundqvist et al., 1999). It was found to be very stable, despite the secular decrease of luminosity (Nasuti et al., 1996; Sandberg and Sollerman, 2009) and the presence of glitches and timing noise. Occasionally, small variations of the pulse shape have been observed (Karpov et al., 2007b). Wavelength-dependent changes of pulsar properties have been reported also by Fordham et al. (2002).

The first optical timing studies of the Crab pulsar were carried out soon after its discovery (Nelson et al., 1970; Papaliolios and Carleton, 1970; Horowitz et al., 1971), showing evidence of secular slowdown, noise and glitches (Boynton et al., 1972). Besides a continuous monitoring of its timing behavior (Lohsen, 1981), much attention was devoted to the short term stability of the optical pulse shape (Karpov et al., 2007a) and to the simultaneous absolute timing at radio and optical wavelengths (Oosterbroek et al., 2006; Oosterbroek et al., 2008). Most notably, Shearer et al. (2003) found that optical pulses synchronous with giant radio pulses (occasional powerful pulses that are a thousand times brighter than average pulses) are 3% brighter on average than those coincident with normal radio pulses.

Short timescale (few minutes) modulations of the phase and amplitude of the optical light curve were investigated by Čadež and Galičič (1996), finding evidence for a 60 s modulation that was interpreted as the pulsar free precession period. Although further measurements are needed in order to confirm this finding (see e. g. the different result obtained by Golden et al. 2000), in principle it could be used to constrain the pulsar moment of inertia and hence the equation of state of nuclear matter. Theoretical models of a freely precessing neutron star were calculated and compared against pulsar observations by Jones and Andersson (2001).

It is widely accepted that, for young pulsars, optical emission is synchrotron radiation from relativistic particles spiraling around pulsar magnetic field lines. For middle-aged pulsars, in addition to the emission from the polar caps heated by impinging current, a significant contribution comes from thermal radiation from the cooling neutron star surface. The basic energy source is the pulsar rotational energy, that is somehow transferred to low-frequency radiation and into accelerating charged particles. The major uncertainty is related to the

---

\* Corresponding author

*Email address:* luca.zampieri@oapd.inaf.it (L. Zampieri).

acceleration mechanism of this relativistic wind. Very little is known about the acceleration site, either at magnetic poles, at the surface or further out near the light cylinder, where particles corotating with neutron star magnetic field lines reach the velocity of light. Precise timing of pulsar light curves in different wavebands is a powerful tool to constrain theories on the spatial distribution of various emission regions. While a time delay between different radio bands measures dispersion due to presence of electrons in the whole space between us and the pulsar, differences in arrival times between the radio and optical or X-ray bands most naturally imply that the emission regions differ in position. It has been shown that the main pulse and the interpulse are not aligned in time in the radio, X-ray and Gamma-ray bands, but the high energy photons lead the radio ones (Kuiper et al., 2003; Rots et al., 2004). At optical and radio wavelengths Oosterbroek et al. (2006) and Oosterbroek et al. (2008) recently performed simultaneous absolute timing measurements and found a  $255 \pm 21 \mu\text{s}$  delay between the radio and the optical pulse (with the optical pulse leading the radio one). However, there does not seem to be universal agreement on the value of this phase difference.

As it is bright and nearby and its timing properties are very accurately known, the Crab pulsar is an ideal target for testing photon-counting instruments in all bands of electromagnetic spectrum. It is used as a standard candle to calibrate both the flux and timing accuracy of optical and high-energy instruments. Thus, we decided to test our novel photon-counter AquEYE (the Asiago Quantum Eye; Barbieri et al., 2009) by performing a sequence of observations of Crab pulsar. Here we report some preliminary results from these observations.

## 2 AquEYE

AquEYE stands for Asiago Quantum Eye and is a very fast single photon-counter based on avalanche photodiodes operated in Geiger mode (SPADs). The design of AquEYE follows that of QuantEYE (the Quantum EYE; Dravins et al., 2005; Barbieri et al., 2009), an instrument conceived for studying second order correlations in photon streams from astrophysical sources, down to the quantum limit. QuantEYE was designed for future very large collecting area telescopes, such as the extremely large European telescope of ESO (E-ELT). AquEYE is mounted at the 182cm Copernicus telescope at Cima Ekar in Asiago. It can record and store arrival times of all detected photons with an absolute precision (referred to UTC) better than 500 ps for hour-long observing sessions Zoccarato et al. (2010). To our knowledge, this instrument provides the most accurate arrival times ever achieved in the optical band.

Each signal from the SPADs is timetagged by a Time to Digital Converter

Table 1

Log of the observations of the Crab pulsar performed with Aqueye mounted at the 182cm Copernicus telescope in Asiago on the nights of October 10-12, 2008. The start time of the observations is the GPS integer second, accurate to better than approximately  $\pm 30$  nanoseconds. The second column is the MJD at the beginning of the observation corrected at the solar system barycenter.

Starting time (UTC)	MJD	Duration (s)
Oct 10, 23:45:14	54749.993034053951089	1078
Oct 11, 01:45:44	54750.076722217817146	1797
Oct 11, 02:23:07	54750.102685217842115	1631
Oct 11, 23:25:08	54750.979164409017692	3597
Oct 12, 23:13:57	54751.971486747642043	3998

(TDC) board (produced by Costruzioni Apparecchiature Elettroniche Nucleari, Italy), that makes use of an external Rubidium oscillator as external reference frequency. This clock is extremely accurate on short term, but has a drift on long periods. To remove this drift, a pulse-per-second (PPS) signal from a GPS unit is given in input to the TDC board and time tagged together with the other recorded events. Then a post-process analysis of the collected PPS allows to determine and remove the Rubidium drift. Future realizations of our instrument will make use of the Galileo GNSS time signal for improving the long term accuracy of our clock.

### 3 Data analysis

During 2008 the Crab pulsar was observed several times with AquEYE. Here we report on results of our analysis of some October 2008 observations, which are of particularly good quality in terms of sky and seeing conditions. For a log of observations, see Table 1. Arrival times of detected photons are corrected to the Solar System barycenter using the software TEMPO2<sup>1</sup> (Hobbs et al., 2006; Edwards et al., 2006). The barycentric corrected arrival times were then processed with the timing analysis software XRONOS<sup>2</sup> (v. 5.21). Following the default convention adopted in TEMPO2, in this analysis we use the barycentric coordinate time (TCB) as system of time.

<sup>1</sup> <http://www.atnf.csiro.au/research/pulsar/ppta/tempo2>

<sup>2</sup> <http://xronos.gsfc.nasa.gov/>

Table 2

Rotational period of the Crab pulsar measured with Aqueye in 2008. The second column is the MJD at mid observation corrected at the solar system barycenter.

Starting time (UTC)	MJD at mid observation	Period (s)
Oct 10, 23:45:14	54749.999284623447164	0.0336216392
Oct 11, 01:45:44	54750.087139828703616	0.0336216424
Oct 11, 02:23:07	54750.113797334172066	0.0336216433
Oct 11, 23:25:08	54750.999988051155317	0.0336216755
Oct 12, 23:13:57	54751.994405470224461	0.0336217117

## 4 Results

We searched for periodicities in the barycentric corrected time series of the observations by folding the data over a range of periods and by looking for a maximum chi-square as a function of period (XRONOS task `efsearch`). We binned the data using 1000 bins per period and a resolution between contiguous periods in the search of  $10^{-10}$  s. The measured periods are reported in Table 2. The start time is the GPS integer second, accurate to better than approximately  $\pm 30$  nanoseconds. For the observation performed on 11 October 2008, starting at 01:45:44 UTC, the period is  $P = 0.0336216424$  s. For comparison, the period at mid observation obtained interpolating the radio Jodrell Bank Crab ephemerides is  $P = 0.0336216423$  s (after transforming from the Barycentric Dynamical Time to the Barycentric Coordinate Time used in TEMPO2). The difference with respect to our measured period is 0.1 ns. We can consider this as an estimate of our present uncertainty on the period measurement in a single observation. Our timing accuracy is comparable to the rotational period change induced by the pulsar spin-down during the observation.

An estimate of the period derivative can be obtained by fitting directly the measurements reported in Table 2 as a function of time with a first order polynomial. We refer the period measurements to mid observation. At the barycentric corrected time  $t_0 = 54749.0$  (MJD) the period and period derivative are  $P = 0.033621602861 \pm 8.7 \times 10^{-11}$  s and  $\dot{P} = (4.2061 \pm 0.0056) \times 10^{-13}$  s/s ( $2\sigma$  errors), within 0.06 ns and 0.005%, respectively, from the Jodrell Bank Crab ephemeris (after correcting from the Barycentric Dynamical Time to the Barycentric Coordinate Time).

In Figure 1 we show the light curve of the Crab pulsar folded over the average period for the 11 October 2008, 01:45:44 UTC. The folded curve has 1000 bins in phase, with a resolution of  $\sim 33.6$   $\mu$ s, and contains data from

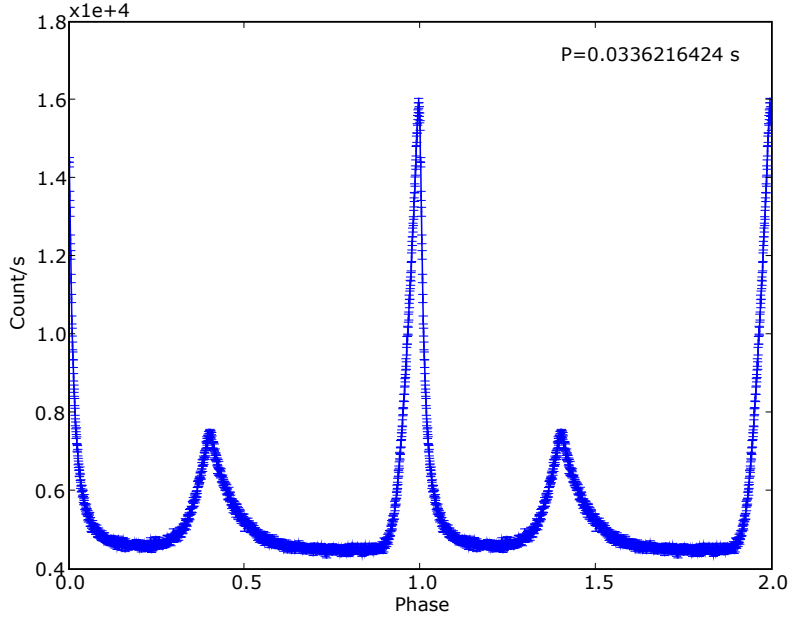


Fig. 1. Folded light curve over the average period of the Crab pulsar for the AquEYE observation performed on 11 October 2008 (01:45:44 UTC). The bin time of the light curve is  $3.362 \times 10^{-5}$  s. For the sake of clarity two rotations of the neutron star are shown.

53,458 pulse periods. The double peak profile of the pulse has an excellent definition and its quality is comparable to that achieved with instrumentation mounted on larger area telescopes. In Figure 2 this pulse profile is compared with that of the fifth observation (Oct 12, 23:13:57 UTC), taken two nights after. The comparison is performed applying a shift in phase and a stretch in amplitude to one of the two curves, estimated using a  $\chi^2$  minimization procedure. The two profiles are clearly overimposed and no significant short term (days) variability is observed (apart, possibly, from a small difference in the trailing edge of the main peak, around phase 0.6, that will deserve further investigation). In Figure 3 we compare the AquEye folded curve with that obtained in 1994 by Beskin et al. (2000), with a photomultiplier having  $3.3 \mu\text{s}$  resolution. The comparison is performed as before, by means of a  $\chi^2$  minimization procedure. In order to better compare the two curves, that of Beskin et al. (2000) was rebinned to 1000 bins in phase. As shown in the plot of the residuals, the profiles are consistent and testify a remarkably stable behaviour, at the level of  $\sim 1\%$  on a timescale of 14 years. There may be some small systematic difference in the profile of the interpulse, but the variation is within our present uncertainty. A similar pulse shape was also recorded in years 1999 and 2003. We do not find evidence of the drastic change and variability of the light curve observed in 2005-2006 (Karpov et al., 2007b).

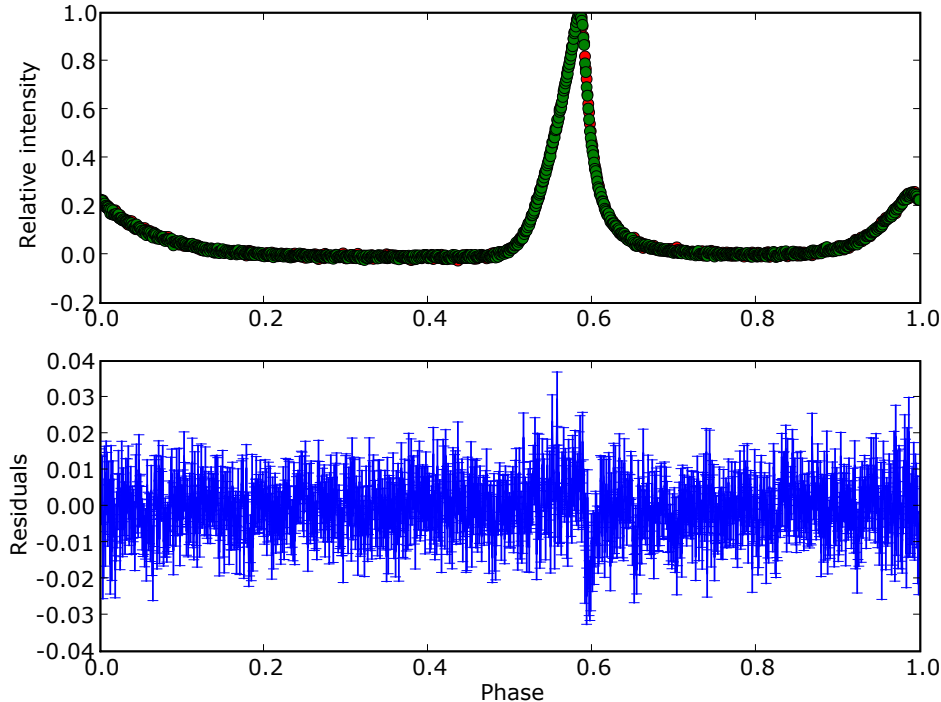


Fig. 2. *Upper panel:* AquEYE folded light curve of the Crab pulsar on 11 October 2008 (*green*; observation starting at 01:45:44 UTC) and on 12 October (*red*; observation starting at 23:13:57 UTC). A shift in phase and a stretch in amplitude was applied to the Oct 11 data. *Bottom panel:* fractional residuals. The reduced  $\chi^2$  of the difference of the two curves is 1.05.

## 5 Conclusions

We observed the Crab pulsar with a novel photo-counter, AquEYE, mounted at the 182cm Copernicus telescope in Asiago. The observations performed on October 10-12, 2008 were of particularly good quality in terms of sky and seeing conditions. The counting statistics allowed us to determine the pulsar rotational period and period derivative with great accuracy from only three nights of data. A full statistical analysis of the time-of-arrival and phase of the main pulse in comparison with those of the Jodrell Bank radio ephemerides is presently under way (Germanà et al., 2010) and may possibly allow us to obtain an independent measurement of the delay between the radio and the optical pulse.

Apart from the changes visible only in 2005-2006 (Karpov et al., 2007b), during the last 14 years the folded light curve of the Crab pulsar was very stable, as we measured a pulse shape essentially identical to that observed in 1994. Any variation is below the sum of the statistical errors of the two

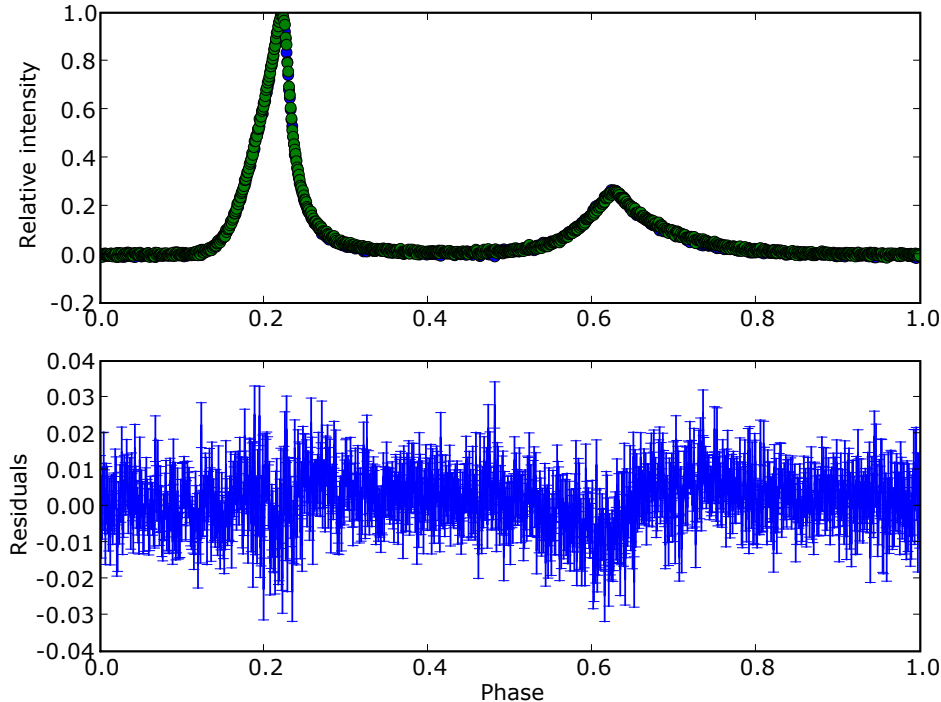


Fig. 3. *Upper panel:* AquEYE folded light curve of the Crab pulsar (*green*; 11 October 2008, 01:45:44 UTC) and the *B* band light curve obtained in 1994 by Beskin et al. (2000) (*blue*). A shift in phase and a stretch in amplitude was applied to our data. *Bottom panel:* fractional residuals. The reduced  $\chi^2$  of the difference between the two curves is 1.3. A similar result is obtained by performing the comparison with the *R* band light curve of Beskin et al. (2000).

curves ( $\simeq 1\%$ ). Since 1994 the frequency of the pulsar changed by more than 0.5% (or, if the dipole radiation loss dominates, the rotational energy loss decreased by more than 2%). Pulse shapes are typically quite stable, unless the pulsar undergoes frequent mode switching, in which case an abrupt change of the pulse with respect to the usual integrated pulse profile may occur at unpredictable times. Such behaviour is observed in some complex profile radio pulsars (mode switching pulsars; e. g. Backer 1970; Bartel et al. 1982). The steadiness and large duty cycle appear to be consistent with the outer gap accelerator model of pulsar emission (Takata and Chang, 2007). Pulse profiles of Crab-like pulsars from the optical through the gamma-ray bands have been investigated within the framework of this model (see e. g. Venter et al. 2009). In particular, Takata and Chang (2007) find that differences in pulse shapes are caused mainly by: differences in inclination angles ( $\alpha$ ) between the spin axis and the magnetic axis; differences in viewing angles; differences in thickness of the emission region. For the Crab pulsar, they found  $\alpha \approx 50^\circ$ . Our data therefore reinforce evidence for decadal stability of the inclination angle  $\alpha$ , the viewing angle and the thickness of the emission region.



Using the experience gained with AquEYE, a new, improved version of the instrument, dubbed IquEYE (Italian Quantum EYE), has already been built and mounted at the ESO NTT. Two runs performed in January and December 2009 permitted to test the instrument and acquire useful data which are now being reduced. We intend to search for possible modulations in the Crab pulsar induced by free precession. At the same time, we are planning simultaneous, high time resolution observations in the radio, optical, X-ray and gamma-ray bands in order to study the delays of the pulse shape among different energy bands. For future realizations, the presently available GPS signal could be supplemented by those of the Galileo GNSS. Having more satellites with different characteristics could help to lower the uncertainties in the start time and improve both the long term stability and accuracy of our timing system.

## Acknowledgments

We would like to thank Andrea Possenti (INAF-Astronomical Observatory of Cagliari) for his help in using the TEMPO2 software. We also thank Massimo Calvani (INAF-Astronomical Observatory of Padova) and Alessandro Patrino (Astronomical Institute, University of Amsterdam) for useful discussions. We are grateful to Sergey V. Karpov for kindly providing us the files of the 1994 light curve of the Crab. This work has been partly supported by The University of Padova, by the Italian Ministry of University MIUR through the program PRIN 2006, by the Program of Excellence 2006 Fondazione CARIPARO, and by the Harrison project of the Galileo supervising authority.

## References

- Backer, D. C., Correlated Subpulse Structure in PSR 1237+25, *Natur*, 228, 752, 1970.
- Barbieri, C., Naletto, G., Occhipinti, T., et al., AquEYE, a single photon counting photometer for astronomy, *J. Mod. Opt.*, 56, 261, 2009.
- Bartel, N., Morris, D., Sieber, W., et al., The mode-switching phenomenon in pulsars, *Astrophys. J.*, 258, 776, 1982.
- Beskin, G., Komarova, V., Plokhhotnichenko, V., The Crab pulsar in UBVR bands simultaneously with 3.3 microsecond resolution, *Nucl. Phys. B Proc. Suppl.*, 80, C1103, 2000.
- Boynton, P. E., Groth, E. J., Hutchinson, D. P., et al., Optical Timing of the Crab Pulsar, *NP 0532, Astrophys. J.*, 175, 217, 1972.
- Čadež, A., Galičič, M., Are the pulses of the Crab pulsar modulated?, *Astron. Astrophys.*, 306, 443, 1996.

- Cocke, W. J., Disney, M. J., Taylor, D. J., Discovery of Optical Signals from Pulsar NP 0532, *Natur*, 221, 525, 1969.
- Dravins, D., Barbieri, C., Fosbury, R. A. E., et al., QuantEYE: The Quantum Optics Instrument for OWL, *ArXiv Astrophysics e-prints*, 2005. Online at <http://xxx.lanl.gov/abs/astro-ph/0511027>.
- Edwards, R. T., Hobbs, G. B., Manchester, R. N., TEMPO2, a new pulsar timing package - II. The timing model and precision estimates, *Mon. Not. R. Astron. Soc.*, 372, 1549, 2006.
- Fordham, J. L. A., Vranesevic, N., Carramiñana, A., et al., Phase-resolved Spectroscopic Imaging of the Crab Pulsar, *Astrophys. J.*, 581, 485, 2002.
- Germanà, C., Zampieri, L., Barbieri, C., et al., AquEYE optical observations of the Crab Nebula pulsar, *Astron. Astrophys.*, submitted
- Golden, A., Shearer, A., Redfern, R. M., et al., High speed phase-resolved 2-d UVB photometry of the Crab pulsar, *Astron. Astrophys.*, 363, 617, 2000.
- Hobbs, G. B., Edwards, R. T., Manchester, R. N., TEMPO2, a new pulsar-timing package - I. An overview, *Mon. Not. R. Astron. Soc.*, 369, 655, 2006.
- Horowitz, P., Papaliolios, C., Carleton, N. P. et al., Optical Time-Of Measurements from the Crab Pulsar: Comparison of Results from Four Observatories, *Astrophys. J. Letters*, 166, L91, 1971.
- Jones, D. I., Andersson, N., Freely precessing neutron stars: model and observations, *Mon. Not. R. Astron. Soc.*, 324, 811, 2001.
- Karpov, S., Beskin, G., Biryukov, A., et al., Short time scale pulse stability of the Crab pulsar in the optical band, *Astrophys. Space Sci.*, 308, 595, 2007a.
- Karpov, S., Beskin, G., Biryukov, A., et al., Pulse variation of the optical emission of Crab pulsar, *ArXiv Astrophysics e-prints*, 2007b. Online at <http://xxx.lanl.gov/abs/0709.2580>.
- Kuiper, L., Hermsen, W., Walter, R., et al., Absolute timing with IBIS, SPI and JEM-X aboard INTEGRAL. Crab main-pulse arrival times in radio, X-rays and high-energy gamma -rays, *Astron. Astrophys.*, 411, L31, 2003.
- Lohsen, E. H. G., Optical timing observations of the Crab pulsar 1968-1979, *Astron. Astrophys. Supplement Series*, 44, 1, 1981.
- Lundqvist, P., Sollerman, J., Gull, T. R., et al., Observations of The Crab Pulsar in The Far-Ultraviolet and in The Optical, *Bulletin of the American Astronomical Society*, 31, 903, 1999.
- Lynds, R., Maran, S. P., Trumbo, D. E., Optical Identification and Observations of the Pulsar NP 0532, *Astrophys. J. Letters*, 155, L121, 1969.
- Nasuti, F. P., Mignani, R., Caraveo, P. A., et al., Spectrophotometry of the Crab pulsar, *Astron. Astrophys.*, 314, 849, 1996.
- Nelson, J., Hills, R., Cudaback, D., et al., Optical Timing of the Pulsar NP 0532 IN the Crab Nebula, *Astrophys. J. Letters*, 161, L235, 1970.
- Oosterbroek, T., de Bruijne, J. H. J., Martin, D., et al., Absolute timing of the Crab Pulsar at optical wavelengths with superconducting tunneling junctions, *Astron. Astrophys.*, 456, 283, 2006.
- Oosterbroek, T., Cognard, I., Golden, A., et al., Simultaneous absolute timing of the Crab pulsar at radio and optical wavelengths, *Astron. Astrophys.*, 488,

- 271, 2008.
- Papaliolios, C., Carleton, N. P., Absolute Time-of-arrival Measurements of Optical Pulses from the Crab Pulsar, *Natur*, 228, 445, 1970.
- Percival, J. W., Biggs, J. D., Dolan, J. F., et al., The Crab pulsar in the visible and ultraviolet with 20 microsecond effective time resolution, *Astrophys. J.*, 407, 276, 1993.
- Rots, A. H., Jahoda, K., Lyne, A. G., Absolute Timing of the Crab Pulsar with the Rossi X-Ray Timing Explorer, *Astrophys. J. Letters*, 605, L129, 2004.
- Sandberg, A., Sollerman, J., Optical and infrared observations of the Crab Pulsar and its nearby knot, *Astron. Astrophys.*, 504, 525, 2009.
- Shearer, A., Stappers, B., O'Connor, P., et al., Enhanced Optical Emission During Crab Giant Radio Pulses, *Science*, 301, 493, 2003.
- Takata, J., Chang, H.-K., Pulse Profiles, Spectra, and Polarization Characteristics of Nonthermal Emissions from the Crab-like Pulsars, *Astrophys. J.*, 670, 677, 2007.
- Venter, C., Harding, A. K., Guillemot, L., Modeling of Gamma-ray Millisecond Pulsar Light Curves Revealed by *FERMI*-LAT, *Proc. XXIemes Rencontres de Blois, "Windows on the Universe"*, in press. Online at <http://arxiv.org/abs/0911.4890>.
- Zoccarato, P., Barbieri, C., Occhipinti, T., et al., The Importance of Accurate Timing of Astronomical Photons, *Adv. Space Res.*, Galileo Special Issue, in press.